Backhaul and Fronthaul for Small Cells 2018

Abstract: This report illustrates how wireless, fiber, and copper options will be used to connect outdoor small cells, and how the shift to 5G will impact the technology. Architectures such as backhaul, midhaul, and fronthaul are covered for 2G through 5G small cells in the five-year forecast, and in each architecture the forecast illustrates how fiber, wireless, and copper options will be used. NLOS and LOS wireless techniques as well as free-space optics are forecasted for connection of small cells.

November 2018

MOBILE EXPERTS

MOBILE EXPERTS

MEXP-BACKHAUL-18

TABLE OF CONTENTS

CHARTS

EXHIBITS

1: EXECUTIVE SUMMARY

Wireless backhaul has been a perennial "great idea" that never gets off the ground, and in this year's report we don't see a major change.

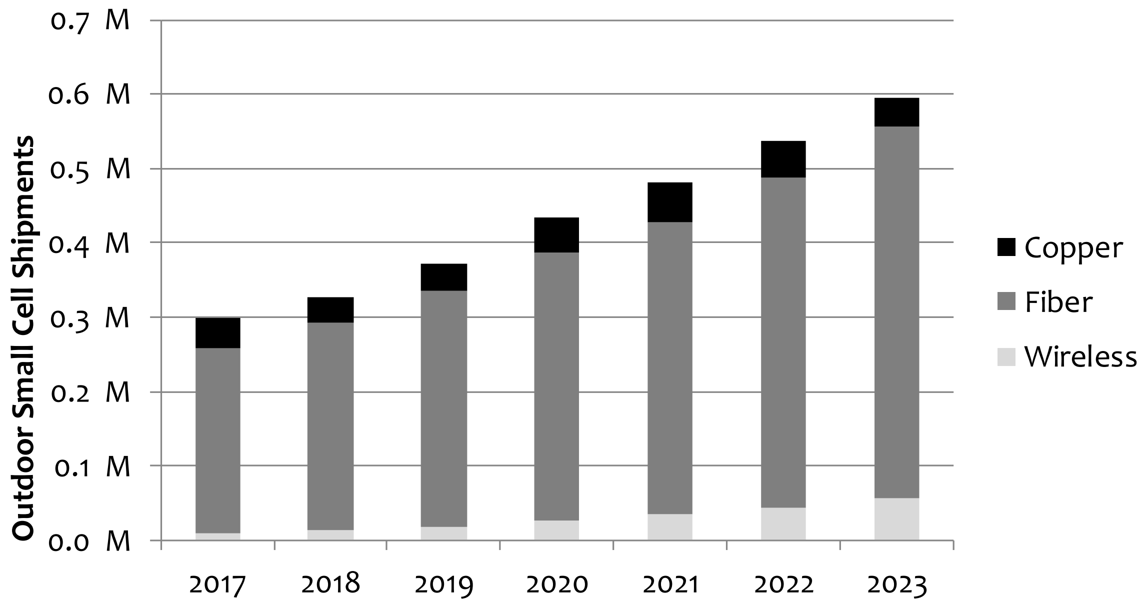
The leading operators worldwide (Verizon, AT&T, NTT DoCoMo, China Mobile, SKT) use fiber to connect remote radio heads and small cells. Why? Because their data growth rates remain high, and they don't anticipate that a skinny pipe will be enough 3-4 years in the future. They anticipate a need for huge bandwidth as end users stream video over 5G access. These companies do not calculate ROI based on a single upgrade, but on a long term roadmap.

Wireless backhaul or fronthaul will have a bigger part to play with second-tier mobile operators. Smaller mobile operators (MTN, Zain, MTS, Bell Canada, Rogers, Telcel, Claro, etc) are more prone to make decisions based on the next upgrade cycle. These regional companies are more likely to be cash-limited. So far, these companies have not made widespread use of small cells because they simply don't have the high density of traffic that Verizon, SKT, and NTT DoCoMo have. We now anticipate that a time will come for smaller operators in less data-hungry markets to use small cells. *When that happens, we will see limited growth for wireless transport to small cells.*

The solutions on the market have not changed much over the years. Fiber options continue to evolve toward 40 Gbps and even 100 Gbps options as we near the market for 5G and Massive MIMO. Wireless options are evolving as well to support 1-2 Gbps even in NLOS cases, and higher throughput for mm-wave options.

Some wireless backhaul suppliers stayed alive by supporting enterprise markets, fixed wireless access, and other related markets. We expect them to be ready for the mobile market when the operators are ready to buy.

Chart 1: Outlook for Small Cell Backhaul/Fronthaul, fiber vs wireless vs copper



Source: Mobile Experts

Operators are currently considering the use of backhaul (with all baseband processing in the small cell), midhaul (where baseband processing is split between the RRH and a data center), and fronthaul (baseband is centralized using a CPRI link). As time goes by, the most likely configuration for transport to small cells/RRH is shifting toward midhaul, as most OEMs prefer that configuration and operators can reap the benefits of reduced transport bandwidth.

By 2023, 50,000 small cells and low-power RRH units shipped will use wireless transport---an increase from a very low percentage this year. Most of these small cells will use wireless for backhaul, not for fronthaul, because the choice to collapse the baseband processing into the radio unit is actually intended to allow easier transport. Other architectures will generally use fiber. We see the potential growth of wireless backhaul as limited now that 5G is approaching, despite the rise of split baseband architectures that will enable and drive wireless use for suburban and second-tier operator requirements.

2: MARKET DRIVERS AND CHALLENGES

Small Cell Market Growth

Small Cells are now an established business, with about 250,000 outdoor small cells deployed in 2018 alone. We've seen deployment in the downtown urban centers move outward, so that this year we can say that small cell deployment is in suburban areas and second-tier cities….not just in Shanghai and New York.

For several years, Mobile Experts has tracked the mobile traffic density of operators, and we've established a good correlation between high traffic density and their use of small cells. In our survey of multiple major mobile operators, we record benchmark data for mobile traffic density in terms of Gigabits per second, per square kilometer, per MHz of licensed spectrum. (Gbps/km2/MHz or GkM). History has shown that when operators reach a level above 0.02 GkM, they tend to add outdoor small cells to the network.

Operators install outdoor small cells on utility poles, buildings, traffic poles, streetlights, bus stop shelters, trash cans, and other 'street furniture'. Outdoor small cells and low power RRH units are typically used to augment capacity in the network, alleviating congestion in the spectrum when GkM traffic density is high.

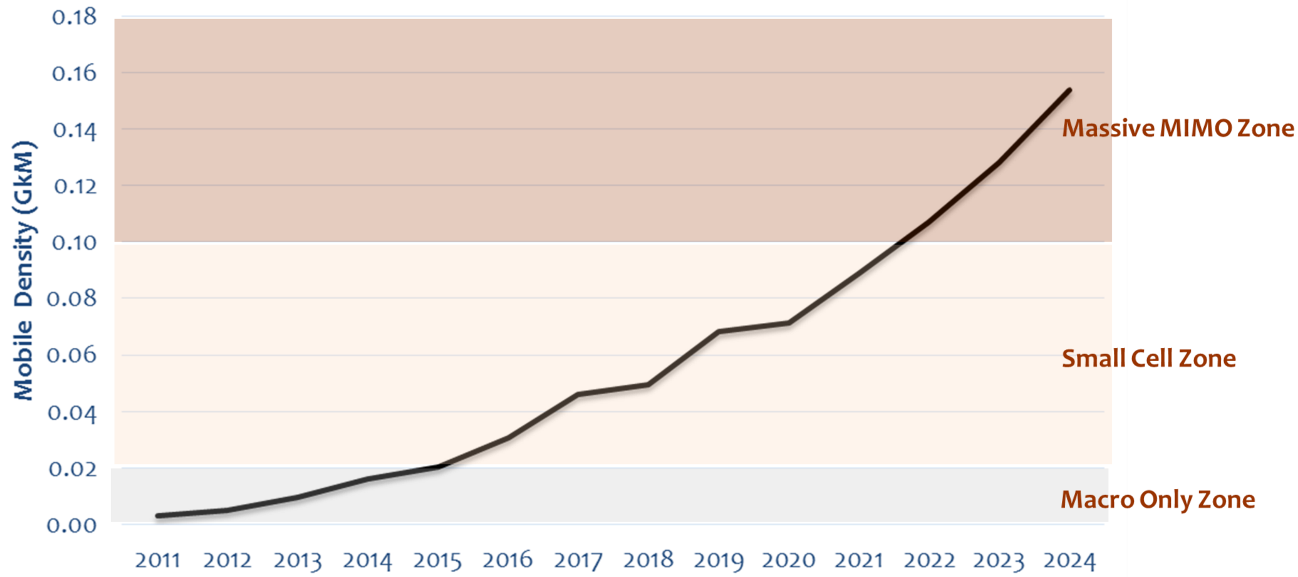
Indoor small cells are typically used in shopping malls, subway stations, and other areas where heavy traffic takes place indoors. Indoor small cells have not been as predictably correlated with traffic density, because operators need to also consider the willingness of the building owner to cooperate, and the need for multi-carrier solutions inside the building.

We focus primarily on outdoor small cells in this report because indoor small cells are not good candidates for wireless backhaul, and virtually all of them are connected via fiber.

Operators choose outdoor small cells for two reasons:

1. Small cells are cheaper than new macro towers, as a way 'densify' or augment the capacity of the mobile network. When new spectrum is scarce, operators move more quickly into small cells because it's the best option to keep up with demand.
2. Mobile operators have recently seen LTE small cells as a way to prepare the network for 5G. Small cells on fiber can establish a grid of site locations that are suitable for mm-wave 5G.

Exhibit 1: Correlation between traffic density and small cell usage



Source: Mobile Experts

The traffic density of the network drives economic decisions by the mobile operators. Above a level of 0.02 Gbps/km2/MHz (0.02 GkM), small cells are the cheapest way to densify. Operators that exceed a level of 0.1 GkM will also need to add massive MIMO to the macro layer. That level of development is still fairly limited to urban centers in Asia, the USA, and northern Europe… so most of the world market still lies at the lower end of this scale.

A few other new developments can also impact the use of small cells. License Assisted Access (LAA) has come to market after years of development and testing, and we expect that LAA will dramatically increase the bandwidth available for each small cell unit. Note that this impacts the backhaul by adding bandwidth, but also reduces the GkM density, possibly delaying the need for additional small cell units.

In the big picture, the main driver for small cells comes down to increasing data demand. We don't see data growth slowing down soon, because the use of mobile video is still in its infancy. As people increasingly binge-watch Netflix over LTE and 5G, we expect that the data usage per subscriber can still increase by a factor of 5 or 10. That means that small cells will continue to expand outward from the urban core, to fill in capacity in suburban, rural, and third-world markets for many years.

Architectural Trends

The preferred architecture in the "small cell" market has changed. Instead of true small cells, which are defined as self-contained units that include all baseband processing for Layers 1-3, mobile operators now prefer various RRH architectures.

Anticipating that each small cell is likely to handle 4-5 LTE bands plus 5G in the future, the operators are convinced that CPRI will become a cumbersome format. A small cell with multiple bands and modes, including LTE, LAA, and 5G will have a capacity in the range of 2-4 Gbps. For a CPRI link, that requirement translates into a data throughput in the 20 -40 Gbps range. They don't want to push the state of the art in terms of data speed on the backhaul without a good reason…and in fact there is no compelling technical reason to stick with CPRI.

Other alternatives have come up (see more background in Section 3) which split the baseband processing and reduce the transport bandwidth requirement dramatically, without affecting the mobile capacity of the system or other factors. Almost all major mobile operators are planning to use some kind of split baseband approach, with centralization of baseband processing for their low-power radio sites as well as macro sites.

In theory, the change to a split-baseband approach would allow for wireless backhaul to be used because the bandwidth requirement is lower. In practice, this change has not helped the wireless backhaul community much because the biggest operators feel that ongoing data growth will put them right back in the 10 Gbps+ range anyway.

Challenges for Wireless Backhaul

There are a few simple reasons that mobile operators have not used wireless backhaul as much as the suppliers would like:

- LAA, 4x4 MIMO, and 5G. Multiple upgrades are queued up, ready to be injected into each small cell site for added capacity. Mobile operators are reluctant to commit to wireless backhaul because they see it as a "skinny pipe" that cannot be expanded later. Fiber is seen as a "fat pipe" that is expandable with improved fiberoptic transceivers in the future.

- Cost: Some operators actually find that fiber is cheaper than wireless bakhaul for them. This is not true everywhere, but certain operators in Asian markets can move quickly to roll out fiber and don't have the exorbitant costs that we see in the Western markets.

- Match with "leading operators" and "following operators": The operators with the highest quality LTE networks are the ones with highest traffic density. The second-tier operators with lower traffic levels haven't needed small cells yet, so we're still waiting to see their approach to small cell backhaul.

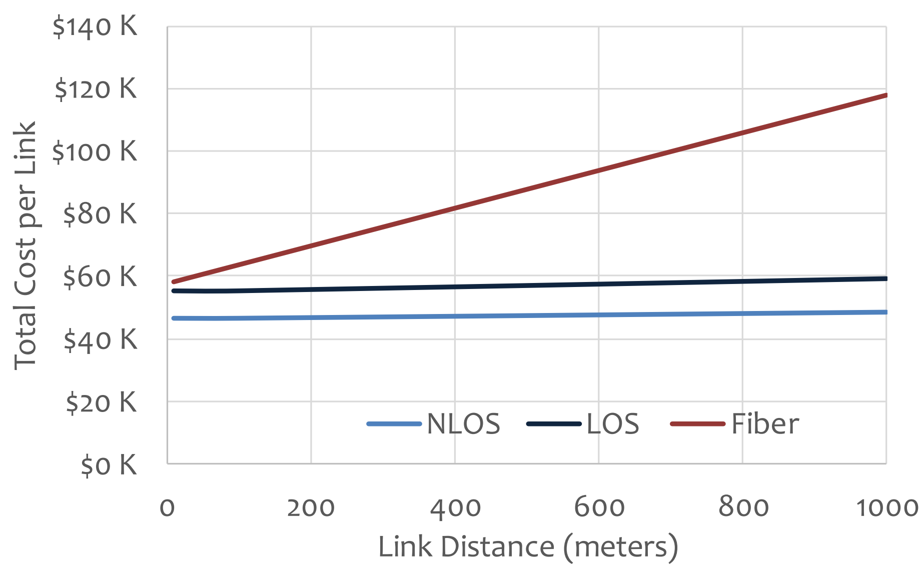
Wireless Transport -- Cost

Backhaul, midhaul, or fronthaul (collectively called "transport") works best on fiber, and that's always the preference of mobile operators due to fiber's reliability, low latency, and huge bandwidth. However, at $60 per meter, the up-front cost of fiber deployment is painful in markets such as the USA and Europe.

Proactive mobile operators with grand 5G plans are pushing ahead with the fiber investment. The thousands of Verizon, SKT, NTT DoCoMo, and Reliance Jio small cells deployed so far have used fiber in 98% of cases. As a result, the early market for wireless backhaul has been dismal.

However, second-tier operators won't necessarily make the same proactive decision to use fiber. On a tighter budget, companies such as Claro, Bell Canada , Telefonica, Orange, and Vodafone have indicated their interest in using wireless transport instead. The key customers for these operators are located in cities with lower ARPU, lower density, and less traffic growth. Wireless backhaul has lower total cost than fiber, so we see a smallish opportunity coming over time.

Chart 2: Cost Comparison for a Second Tier Operator, NLOS vs LOS vs Fiber

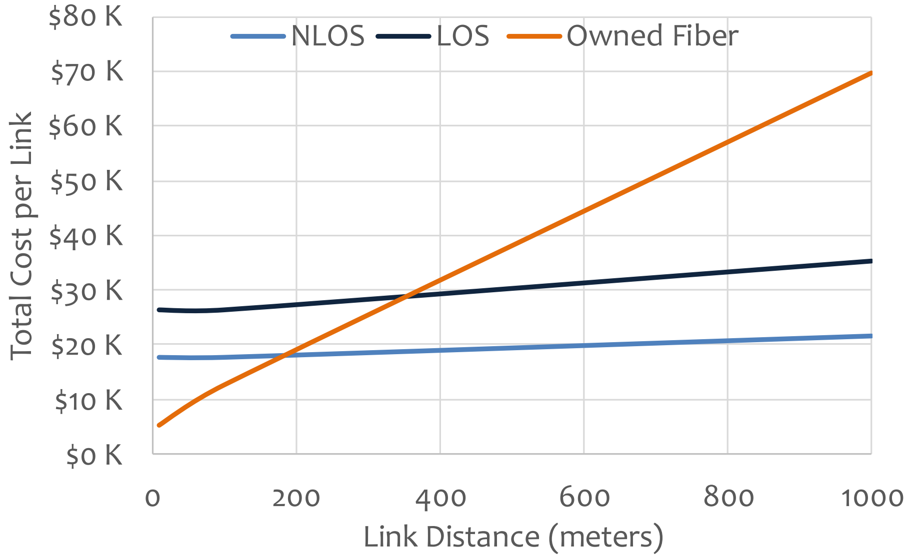


Source: Mobile Experts. Assumes leased fiber for 10 km to data center

Chart 2 implies that wireless is always cheaper than fiber. This conclusion appears to be true for second-tier operators that have no fiber of their own. However, for top-tier operators, there are cases where fiber can be a much cheaper solution.

Chart 3 illustrates the different economics of owned fiber. As one example, Verizon Wireless bought 26,000 miles of fiberoptic cable along with XO Communications, giving Verizon excellent access to fiber in cities such as Seattle, Los Angeles, and New York. In these cases, the fiber network includes “dark” capacity which can be considered to be “free” by Verizon. (In truth, there is opportunity cost for Verizon to turn away potential lease revenue, but this factor is very difficult to quantify).

Chart 3: Cost Comparison for a Top Tier Operator, NLOS vs LOS vs Owned Fiber



Source: Mobile Experts. Assumes the operator has dark fiber available

So, we see an opportunity for wireless backhaul for operators that have their own fiber assets very close to the street furniture, in markets where mobile data growth is not extreme. Think of cities where traffic density is less intense than in top metropolitan centers… second tier cities in Russia, Brazil, South Africa, and other locations where data growth is only now starting to reach the small cell threshold.

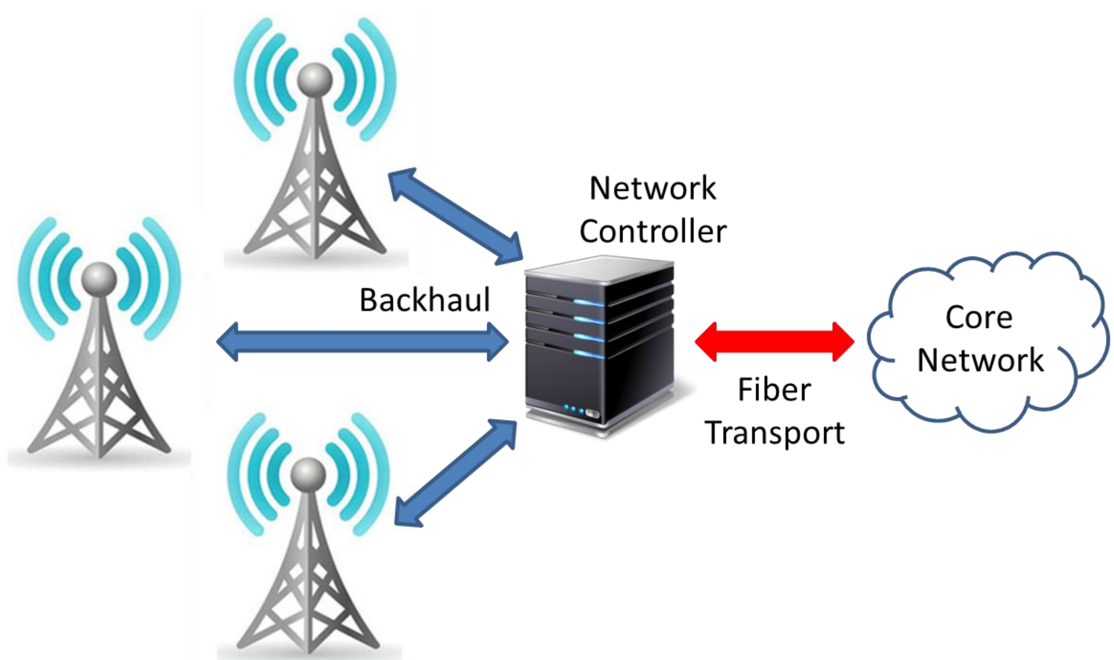
3: TECHNOLOGY: BACKHAUL, MIDHAUL, FRONTHAUL

For the past 20+ years, all of the baseband processing (for Layers 1-3) was done in a network controller. Then, small cells were introduced, moving Layers 1-3 into the radio unit without changing the basic partitioning of the layers themselves.

This approach, known as "backhaul", uses CPRI or a similar serial interface between the Layer 1-3 processing in the small cell and the Layer 4-7 processing in the centralized data center. In theory, CPRI and a similar format known as OBSAI were supposed to create an open market for radio hardware, with interchangeable radio heads between vendors. This dream never happened, but the CPRI serial interface became a de facto standard anyway.

Today, this legacy format does not make much sense anymore. Using a serial interface results in huge bandwidth for Carrier Aggregation or any small cell that includes unlicensed bands with substantial throughput. The data stream to support the serial interface quickly multiplies to 40 Gbps or more for advanced, high-throughput small cells, making implementation on fiber impractical.

Exhibit 2: Backhaul for 2G and 3G Microcells and Picocells



Source: Mobile Experts

Backhaul—For Small Cells

The strict definition of "Small Cells" requires the radio unit to include all Layer 1-3 baseband processing, so that the radio unit itself operates fairly independently from the rest of the mobile network. The Mobile Experts forecast includes five categories of Small Cells, including:

- Residential femtocells;
- Enterprise Small Cells;
- Indoor Carrier Small Cells;
- Outdoor Carrier Small Cells (aka Metrocells); and
- High Power Outdoor Small Cells (aka Rural Small Cells);

The first three (Residential, Enterprise, and Indoor Carrier) are used indoors and we assume that they all use either fiber or Ethernet backhaul. Because of this, we exclude these three categories from this analysis of wireless backhaul adoption.

Outdoor small cell hetnet deployments include radio/baseband enclosures that are placed on the sides of buildings, water towers, lamp poles or other "street furniture". Backhaul is used to connect the small cell to some form of aggregation point before connection back to the core network.

Exhibit 3: A Base Station NLOS Backhaul example

Source: Tarana

Deploying tens of thousands (or even hundreds of thousands) of these outdoor small cells can be problematic if copper or fiber backhaul is planned. While the mobile operator can arrange for the use of any streetlight in the city in one contract, it's not so simple to dig trenches to thousands of street locations overnight. Reliance Jio planned to deploy tens of thousands of small cells with armies of laborers digging trenches in India, but even under those conditions they found time-to-market to be a big challenge.

Running fiber or copper to each utility pole or streetlight can also be quite expensive. Digging trenches in a city environment can cost between $50/m and $100/m in most locations, with a typical run between 100-400 meters for each small cell. This cost can easily outweigh the cost of the equipment itself. Some locations are either prohibitively expensive, or simply impossible due to the historic nature of the cobblestone streets or other local political reasons.

Mobile operators are quickly moving to multiple bands, carrier aggregation, and LAA in outdoor small cells, so the simple 80 Mbps throughput specification is quickly rising to the 1 Gbps level. Rural applications will remain as relatively low bandwidth implementations, although rural backhaul may use a "mesh" configuration in which each small cell is expected to aggregate the traffic for multiple small cells.

Equipment cost is one challenge for wireless backhaul techniques. Fiber is the preferred alternative, but it's expensive. Major carriers have set a target of $2,000 per link for wireless backhaul equipment, and fiber costs much more than $2,000—even for a dense urban deployment. Despite the higher cost, fiber is still used in the major deployments so far. For large-scale deployments, it's likely that wireless pricing will need to come down to about $1,400 per link.

Wireless small cell backhaul is challenging at a technical level. For example, line of sight (LOS) is not always available. Macrocell wireless backhaul solutions typically require LOS links, in order to get the reliability and throughput required. However at the street level, in dense urban areas (the "urban canyon"), a direct LOS wireless path to the backhaul hub locations is often not feasible. Also, the close proximity of wireless backhaul links, operating on similar frequency bands, will mean that interference between collocated and adjacent links will need to be carefully managed. Frequency reuse presents a challenge, because in NLOS configurations the aggregate capacity can be limited.

In addition, environmental and aesthetic concerns will require that outdoor wireless units should be essentially invisible to the general public. Mounting to lampposts and utility poles, or hung from utility wiring, will require robust installations that can withstand mount movements (for example, wind sway), whilst maintaining good wireless connectivity. Space constraints and operational costs will likely favor small cell base station and backhaul solutions integrated into common hardware enclosures.

For these reasons, many of the conventional microwave wireless backhaul solutions, which operate point-to-point (PTP) with strong LOS characteristics using highly directional antennas, will not be successful for small cell backhaul applications. As discussed later, there are a number of newer wireless technologies, particularly those supplying non-LOS operations in the sub-6 GHz bands and also the very high capacity 60 GHz and above mm-wave radios, which are becoming commercially available and can satisfy many of these small cell backhaul requirements.

Fronthaul—for CPRI Remote Radio Heads

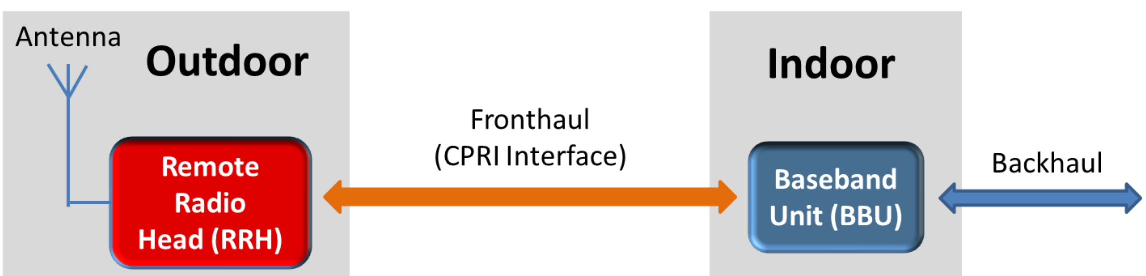
Fronthaul is defined as the connection between a remote radio head (RRH) and a baseband unit (BBU) in a distributed base station. The RRH can be located:

- at the top of a tower (macro base stations are often deployed this way),
- outdoors on the side of a building or street furniture, or even
- indoors (using, for example, a low power RRH).

For the purposes of this market study, we consider only the fronthaul links for BBUs that are co-located remotely with other BBUs in a centralized "baseband hotel". Remote Radio Heads using CPRI protocol (Common Public Radio Interface) for the serialized digital interface are common in Korea and Japan, and are generally recognized as an architecture which sets up the operator for future implementation of virtualized RAN baseband processing.

CPRI supports various line speeds of multiples of about 600 Mbps, up to 10 Gbps, with future versions on the way for 40 Gbps and 100 Gbps using DWDM fiber. Common CPRI data rates being used today include 1 Gbps, 3Gbps, 6 Gbps, and 10 Gbps.

Exhibit 4: Remote Radio Head Fronthaul using CPRI Interface



Source: Mobile Experts

By separating the digital baseband and RF radio heads, and especially by centralizing the BBUs, the CPRI RRH architecture provides for a more efficient use of RAN resources than distributed Small Cell architectures. For example, CoMP and eICIC, among other LTE-Advanced features, can be coordinated for higher perfomance when implemented centrally.

The downside of the CPRI interface is that the connection requires very high data rates, as well as low latency and jitter. As such, strong demands are placed on the technologies required to provide fronthaul connectivity. Fiber optics are generally used because of the high throughput and low latency requirements.

Wireless fronthaul solutions are a possible alternative to fiber for CPRI RRHs. Vendors in the 5.8 GHz unlicensed bands and the mm-wave space are now proposing wireless alternatives to fiber for such fronthaul applications. These can support the gigabit-per-second CPRI interface requirements, as well as latency and jitter specifications. Expect to see wireless as a solution wherever fiber is impractical in a local installation.

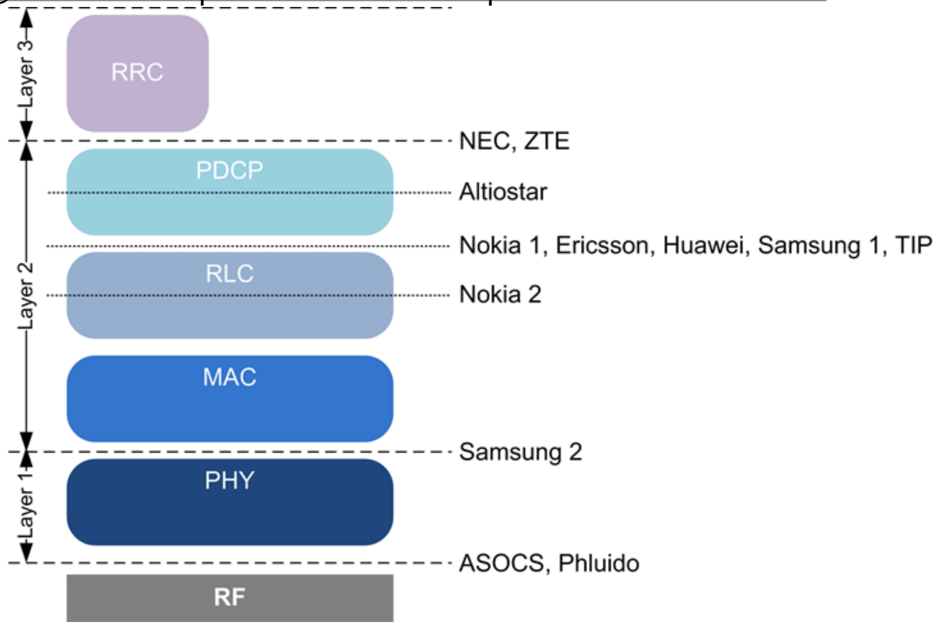
Midhaul—eCPRI and Split-baseband RRH units

Because of the high throughput, low latency, and low jitter requirements of the CPRI interface, the expense and long lead time of fiber have become limiting factors on the growth of the small base station market. All major OEMs (and a few startups) are now developing split-baseband architectures which break up the baseband processing, inserting some processing in the radio node to handle PHY operations and scheduling functions in the MAC. Other baseband processing is generally done in the central pool of BBUs.

These changes are codified in CPRI's latest release of the eCPRI specification in August 2017. The eCPRI spec defines a method to use Ethernet for transport of traffic in a packet-based method. Huawei, Ericsson, NEC, and Nokia all participated in the specification development and worked to define "functional partitioning" of cellular base station functions. In theory, this opens up the possibility of interoperability between RRH units and BBU units from different vendors….but we don't believe that this will really happen in the market, because each vendor still has many proprietary algorithms in operations, management, alarms, beamforming, handovers, and other areas that are not adequately addressed by eCPRI.

This new architecture reduces the throughput, latency, and jitter requirements on the transport link and can enable the use of Ethernet or wireless backhaul, while retaining high performance in LTE-Advanced coordination functions between base stations. (CoMP and eICIC can still work very well).

Exhibit 5: Each OEM's preferred baseband split for Mobile "Midhaul"



Source: Mobile Experts

At least seven different possible baseband splits are under investigation today, with a variety of choices that each OEM will use to differentiate their products under various conditions in the field. The Small Cell Forum is promoting the FAPI interface, in which the MAC and PHY are split. In the end, the most likely outcome is a variation of FAPI in which scheduling functions in the MAC are also included in the on-board processing of the radio head—because this approach will make sync and latency requirements easier to meet in the field.

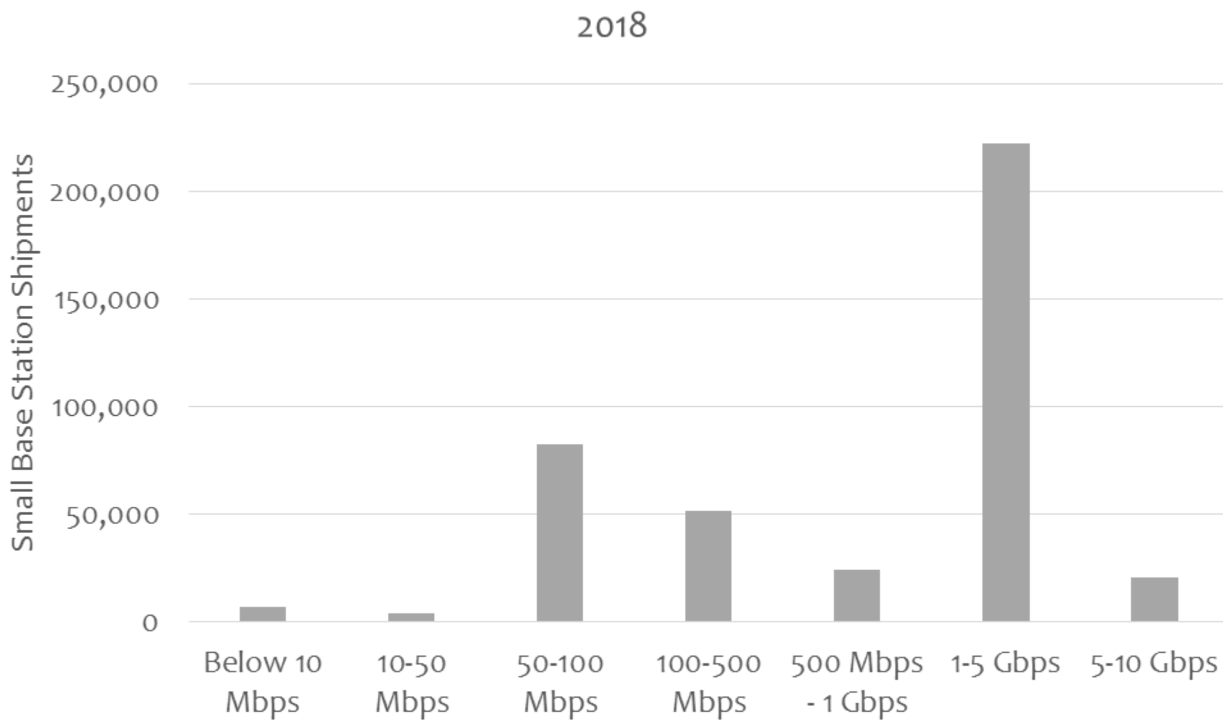
Higher Throughput Required

Mobile operators are starting to rely more heavily on small cells to carry a heavy traffic load. The early days of single-band small cells for coverage holes are over. Now, most small cell deployment is moving toward multi-band devices and the level of sophistication is moving up, with a long list of features that drive higher throughput:

- Carrier Aggregation
- CoMP
- 4x4 MIMO
- Wi-Fi integration
- LAA integration
- CBRS integration

Because most small cells are actually remote radio heads deployed on CPRI today, that means that the existing market is already focused on transport requirements in the range of 1-2 Gbps.

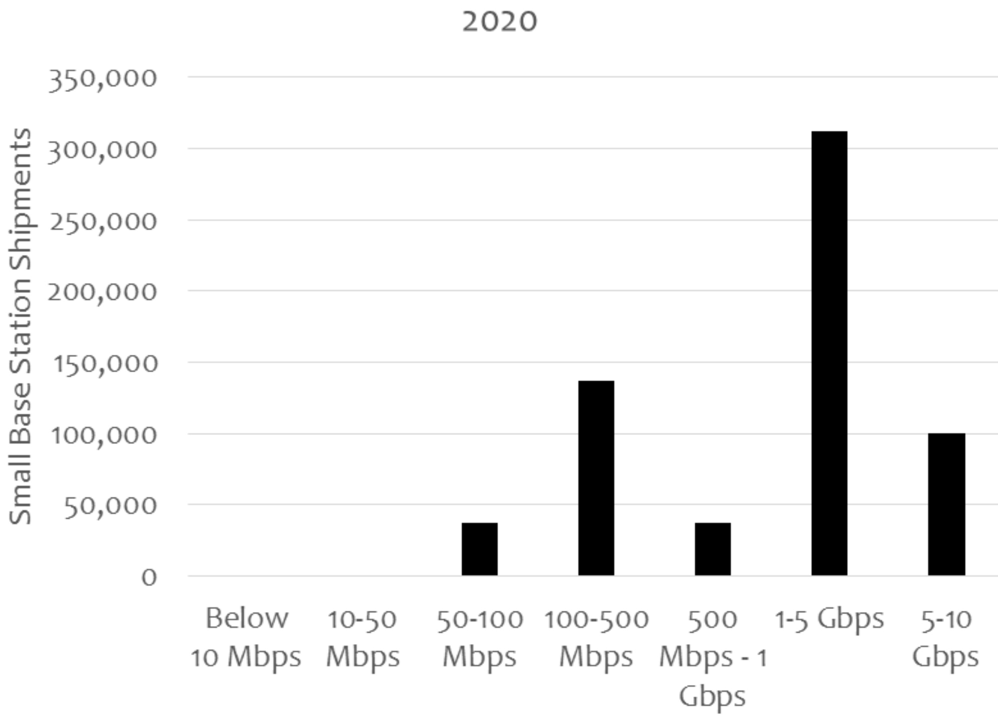
Chart 4: Throughput Requirements in Outdoor Small Base Stations, 2018



Source: Mobile Experts

Over the next two years, LAA and other features will be added to increase the transport bandwidth requirement, but split-baseband RRH units will also enter the market, offsetting the rise in transport data speed. But as the overall small cell market grows, not all of them will have blazing speed requirements. We expect a segment to remain in suburban or other applications where 100-500 Mbps will be adequate.

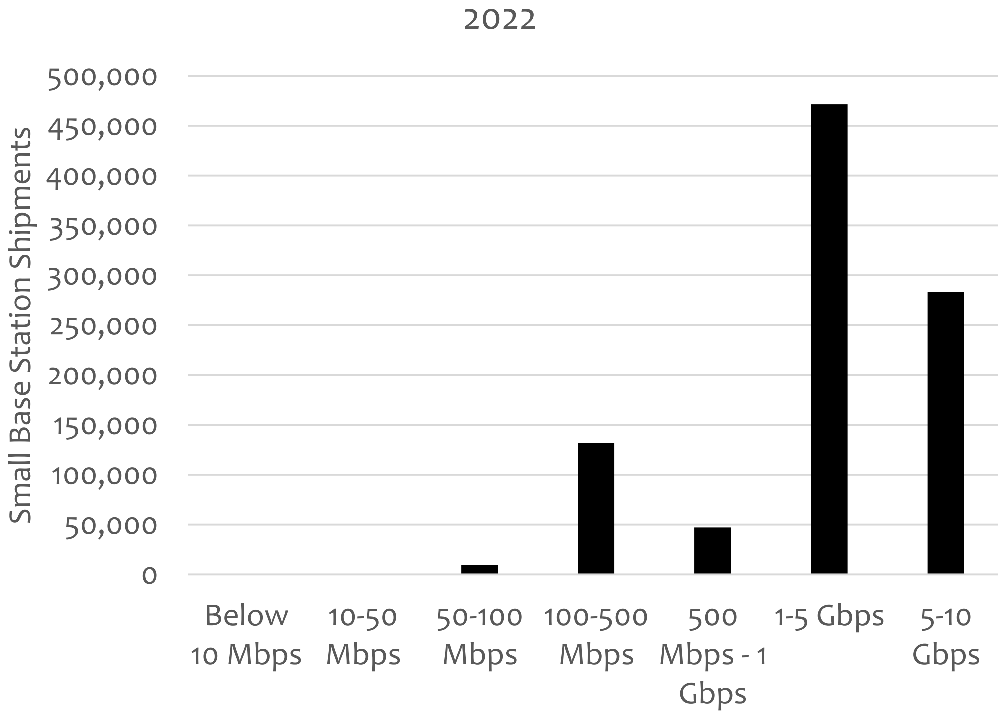
Chart 5: Throughput Requirements in Outdoor Small Base Stations, 2020



Source: Mobile Experts

Then, five years from now we expect to see full utilization of LTE-Advanced features, with many small cells running Gigabit LTE and driving transport requirements into the 5-10 Gbps range. We will still see some small cells that are fully integrated (L1-L3) but these will in many cases include multiple bands for at least a 100-500 Mbps data requirement in the backhaul.

Chart 6: Throughput Requirements in Outdoor Small Base Stations, 2022



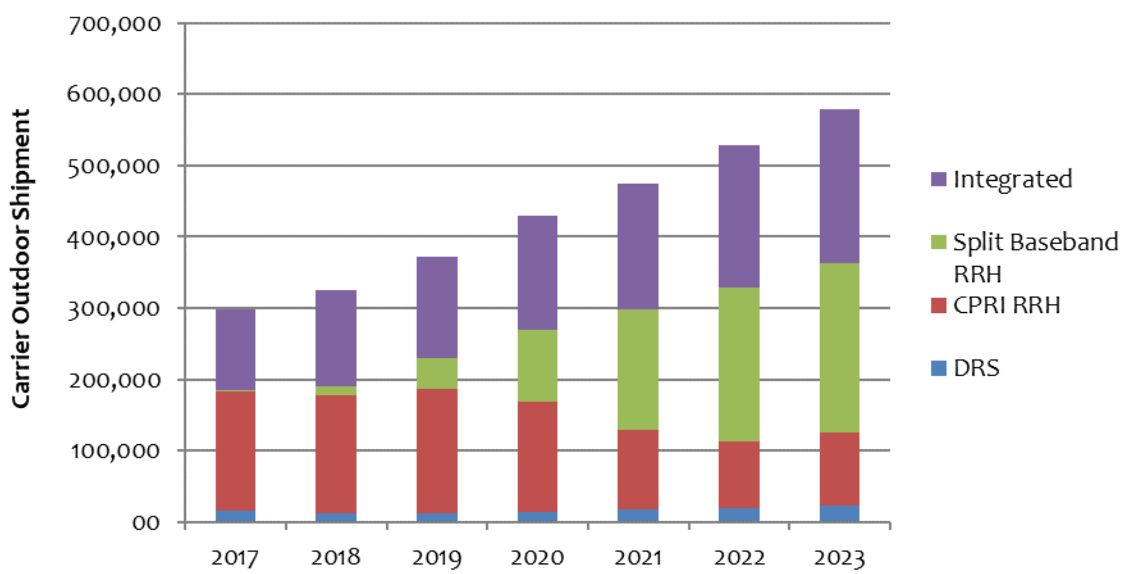
Source: Mobile Experts

4: BACKHAUL, MIDHAUL, AND FRONTHAUL FORECAST

Outlook for Small Cell Growth

Outdoor small cells are in most rich cities over 10 million in population today, and the numbers are growing surprisingly smoothly. About 330,000 units shipped this year (2018) based on heavy use in LTE capacity densification. As mobile data traffic continues to rise, additional cities and some suburban areas will reach the threshold level of traffic density that justifies use of small cells. the numbers will continue to rise steadily.

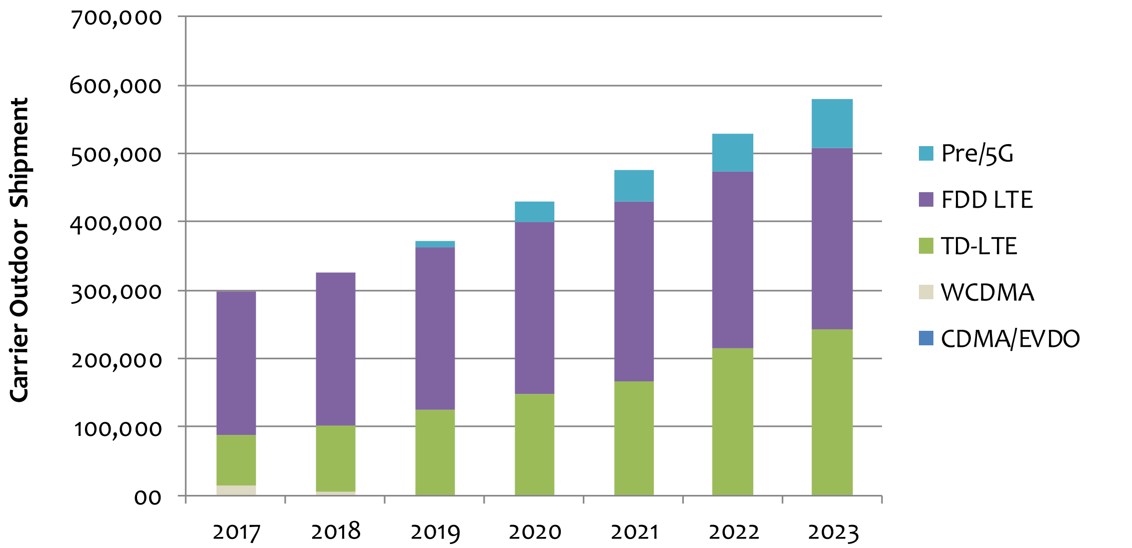
<u>Chart 7: Outdoor Small Cell shipments, by architecture, 2017-2023</u>



Source: Mobile Experts

Most small cell shipments today use FDD-based LTE, and some operators such as China Mobile, Softbank, and Sprint use TD-LTE. We've already seen some mm-wave 5G cells deployed on streetlights in the USA… and we will see other 5G deployment growing over the next 3-5 years. Note that below 6 GHz, we expect macro base station deployment to dominate the market through 2022, so 5G small cell growth will come later during the 'densification' phase.

Chart 8: Outdoor Small Cell shipments, by 2G/3G/4G/5G, 2017-2023



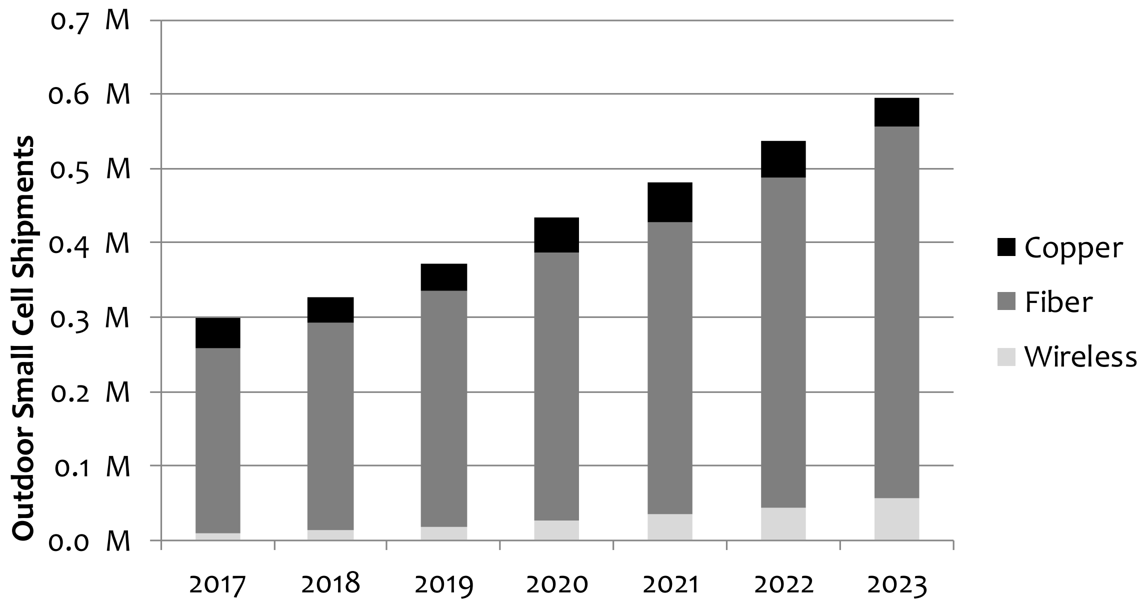
Source: Mobile Experts

Looking more closely at the transport choices for small cells, there's a wide variety. Copper was the early choice for 2G/3G microcell and picocell market, with T1/E1 lines for backhaul in many cases. However, after about 2015 nobody was using copper as a primary strategy anymore, despite G.fast technology to speed up performance.

Fiber has taken off quickly with small cell deployment in Asia, and will continue to dominate the lion's share of small cell connections. Fiber is simply the default solution in Asia, and has become the main choice in the USA as well.

Wireless, in general, will take the role of filling gaps in backhaul or midhaul where fiber is difficult to implement, and possibly in supporting small cells for regional and third-world operators.

Chart 9: Outdoor Small Base Station connections, by technology, 2017-2023

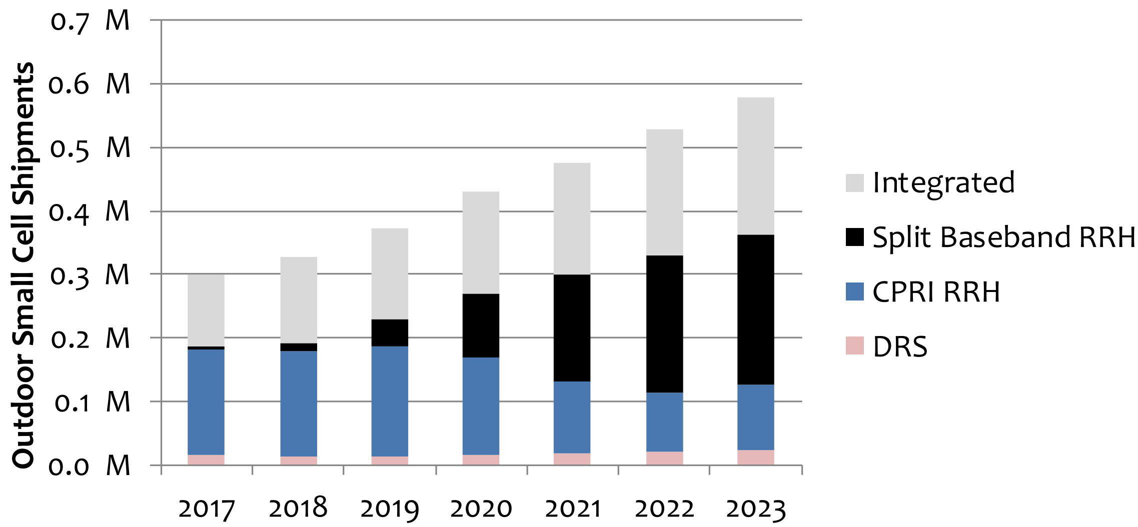


Source: Mobile Experts

Without a doubt, the market is shifting to split-baseband architectures, moving away from CPRI. Accordingly, we predict a strong shift from Backhaul and Fronthaul toward Midhaul, with relaxed throughput and latency requirements compared to CPRI.

- Backhaul includes traditional 2G/3G microcells and picocells, as well as the low bandwidth connection for LTE small cells that include their baseband processing.
- Midhaul serves split-baseband radio heads where the PHY and some MAC functions are computed in the radio node, but other baseband processing is located in a centralized location.
- Fronthaul refers to units that use CPRI or another serialized I/Q format to connect a radio unit with no baseband processing.
- Distributed Radio Systems (such as Radio Dot and LampSite) used twisted-pair copper cable to transport a simple RF signal along a short distance. In the DRS architecture, the copper cabling is kept to very limited bandwidth as only an RF signal is transported over a short distance to a hub, which converts to CPRI or split-baseband for longer distance transport.

Chart 10: Outdoor Small Base Stations: Backhaul, Midhaul, and Fronthaul, 2017-2023

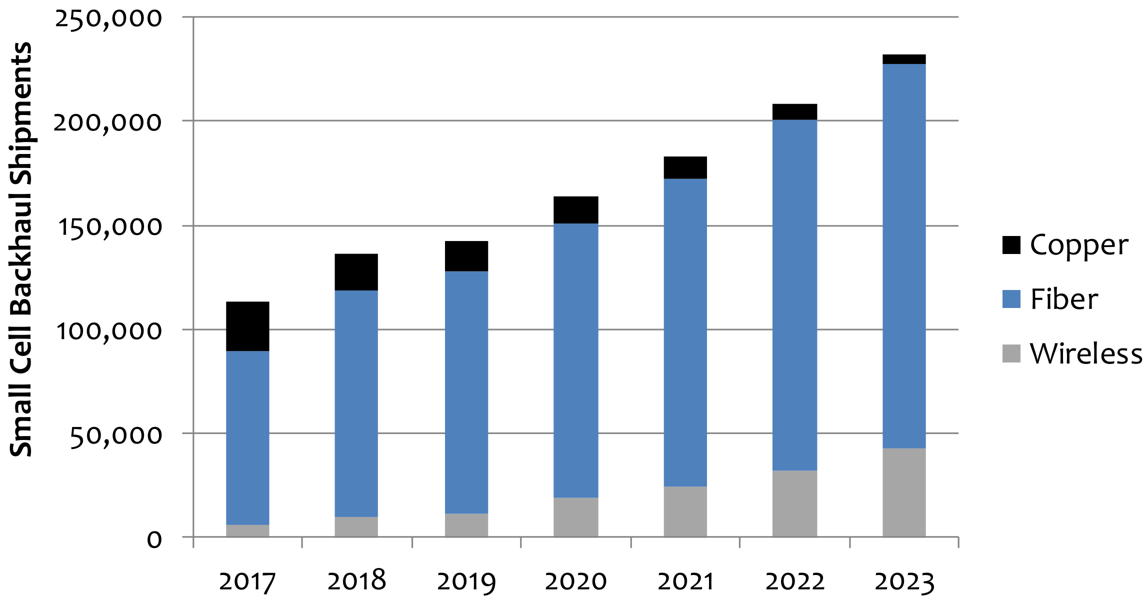


Source: Mobile Experts

Backhaul Forecast

In 2018, backhaul represented 34% of transport for outdoor small cells. This fraction is coming down quickly, as operators are moving away from integrated small cells toward RRH architectures in LTE deployment, centralizing baseband processing for coordination between the macro layer and the small cell layer. Fronthaul has quickly taken the lead, with fiber dominating the physical media.

Chart 11: Backhaul Technology Used for Outdoor Small Base Stations, 2017-2023



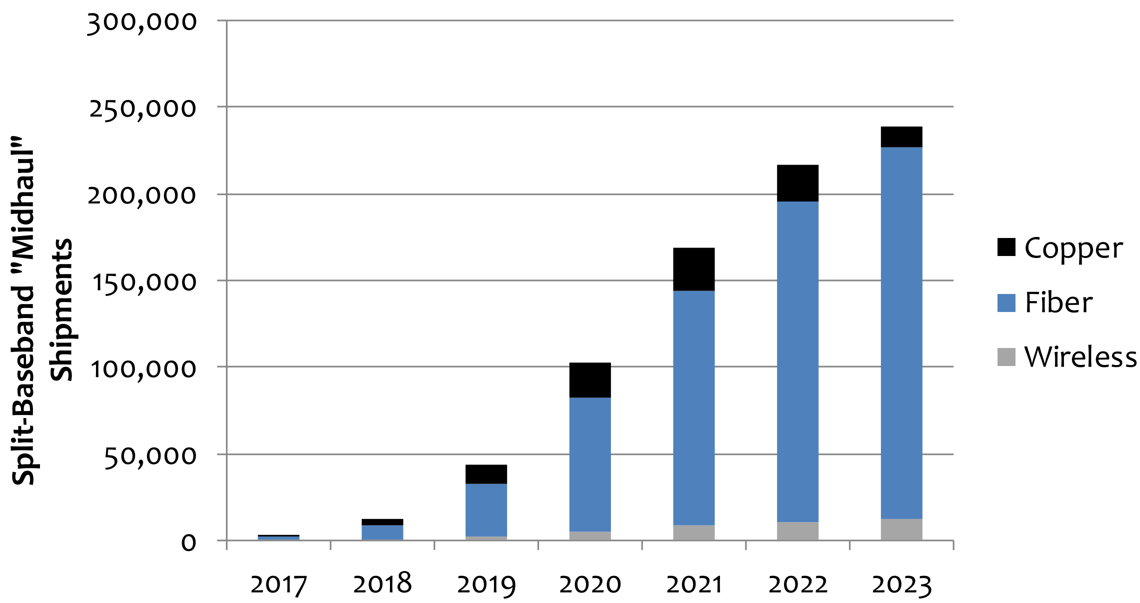
Source: Mobile Experts

Midhaul Forecast

The “Split baseband” architecture is now coming into the market, with about 12,000 small cells shipped during 2018 using this approach. Operators are trying to force this architecture into a standardized format through multiple initiatives (eCPRI, TIP, ORAN) but at the same time they are starting to buy proprietary split-baseband products and deploying them to the field.

As we’ve forecasted in the past, midhaul is happening and it’s quickly becoming the dominant form of transport for small cells. We expect this architecture to dominate the high-capacity, high-dollar value segment of the market, representing about 40% of the total shipments of small cells in 2023.

Chart 12: Midhaul Technology Used for Outdoor Small Base Stations, 2017-2023



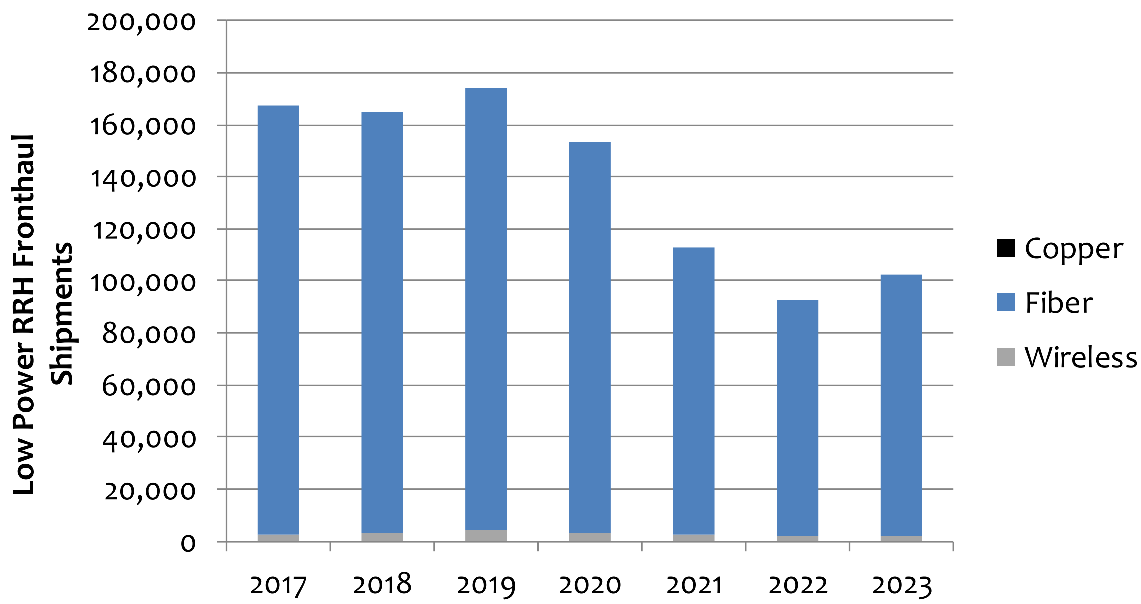
Source: Mobile Experts

Fronthaul Forecast

Fronthaul is considered the 'traditional' way to deploy small cells, with CPRI as the primary standard for the data interface between RRH and baseband unit. Fronthaul almost always uses fiber due to the high throughput requirement on the serialized data. Over time, we expect fiber to continue to dominate due to the increasing bandwidth in the radio head and the corresponding extreme bandwidth requirements in a full CPRI implementation. For anybody using CPRI, only fiber will give the 40 Gbps or even 100 Gbps performance that will be required.

Wireless fronthaul will be used only in niche cases. Natural obstacles such as rivers or canyons may present a difficult challenge for fiber. Human barriers such as historic buildings or cobblestone streets may bring legal challenges. As a result, we think of wireless fronthaul as a case-by-case solution.

Chart 13: Fronthaul Technology Used for Outdoor Small Base Stations, 2017-2023



Source: Mobile Experts

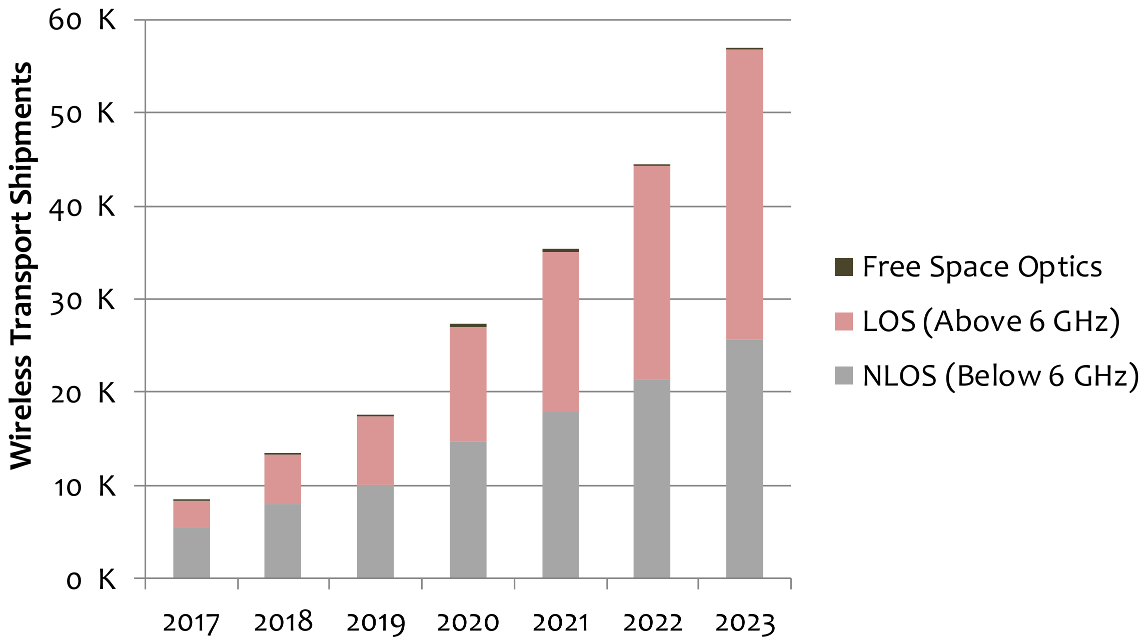
Wireless Transport Forecast—the Technology View

If we choose to segment the market in a different way, putting wireless backhaul/midhaul/fronthaul together, we can consider how wireless transport will develop as a whole. There are three major technologies to consider:

- Non Line of Sight (NLOS) techniques, generally used below 6 GHz;
- Line of Sight (LOS) techniques, generally above 6 GHz in the microwave and millimeter-wave bands; and
- Free-space optical techniques, using lasers for high-bandwidth wireless communication.

Enterprise markets have sustained all three of these techniques, with businesses at various levels of bandwidth choosing between the three technology choices. Each technology has its own niche, with differing enterprise requirements for throughput, cost, latency, reliability, and range. In carrier networks, NLOS and LOS approaches are preferred, and the Free Space Optics suppliers have achieved very little traction. We expect that LOS millimeter-wave systems will grow in importance over time, as bandwidth requirements grow.

Chart 14: Wireless Transport Shipments: NLOS, LOS, and Optics, 2017-2023



Source: Mobile Experts

5: ACRONYMS

2G	Second Generation
3G	Third Generation
3GPP	Third Generation Partnership Project
4G	Fourth Generation
5G	Fifth Generation
Abis	Backhaul interface connecting the BTS base station with the BSC controller in a 2G GSM network
BBU	Base Band Unit
CAGR	Compound Annual Growth Rate
CAPEX	Capital Expense / Expenditure
CBRS	Citizens Band Radio Service (3.5 GHz)
CDMA	Code Division Multiple Access
CoMP	Coordinated MultiPoint
CPRI	Common Public Radio Interface
E1	A copper telecom line at 2 Mbps
eCPRI	CPRI over Ethernet
eICIC	Enhanced Inter-Cell Interference Coordination
FAPI	Femtocell Application Platform Interface
FSO	Free Space Optics
HetNet	Heterogeneous Network
I_{ub}	Backhaul interface connecting the NodeB base station with the RNC controller in a 3G UMTS network
LAA	License Assisted Access
LOS	Line Of Sight
LTE	Long Term Evolution
LTE-U	Long Term Evolution in the Unlicensed Band
MAC	Medium Access Control (Layer 2 in LTE stack)
MuLTEFire	LTE in an unlicensed band without a licensed LTE anchor
NLOS	Non Line of Sight
OBSAI	Open Base Station Architecture Initiative
OpEx	Operation Expense / Expenditure
PHY	Physical layer in LTE stack
PMP	Point to Multi-Point
PTMP	Point to Multi-Point
PTP	Point to Point
RAN	Radio Access Network
RF	Radio Frequency
RNC	Radio Network Controller
RRH	Remote Radio Head
S1	Backhaul interface connecting the eNodeB base station with the core network in a 4G LTE network

SNR	Signal to Noise Ration
SON	Self Optimizing Network
T1	A copper telecommunications line at 1.5 Mbps
TCO	Total Cost of Ownership
UMTS	Universal Mobile Telecommunications System
UNII	Unlicensed National Information Infrastructure
WCDMA	Wideband Code Division Multiple Access
Wi-Fi	Wireless Fidelity
WiMAX	Worldwide Interoperability for Microwave Access

6: METHODOLOGY

To create estimates and forecasts for the Small Cell market, Mobile Experts relies on direct input from more than 55 industry sources, with many different mobile operators contributing to the overall analysis to give a detailed global view of the market. Mobile Experts built a "top down" forecast based on direct input from mobile operators and based on trends in end-user demand for mobile services. Then, Mobile Experts built a "bottom up" forecast through discussions with OEMs and semiconductor suppliers in the supply chain. Roughly 45 component suppliers, integrators, and OEMs participated in this phase of the survey. Mobile Experts also used financial disclosures from publicly traded companies to assemble a quantitative view of the equipment market.

Based on the small cell forecast, Mobile Experts then interviewed several mobile operators and more than 20 suppliers to understand the dynamics of backhaul technology choices. Mobile Experts has been able to review the trial results and demos for several backhaul vendors, and has conducted an in-depth cost analysis of wireless backhaul solutions which guided our conclusions as to the extent of wireless adoption.

Exhibit 6: Definitions for each type of Small Cell

Definitions	RF Power	Backhaul	Architecture
Macrocell	40W+ composite	Operator managed	Closely controlled cells
Traditional Microcell	5.1-39W composite	Operator managed	RNC or BSC architecture (2G/3G)
Traditional Picocell	300 mW to 5W composite	Operator managed	RNC or BSC architecture (2G/3G)
Low power CPRI RRH	up to 1W per antenna	CPRI, OBSAI, ORI to separate baseband unit	No baseband processing in radio unit
Low Power Split-Baseband RRH	up to 1W per antenna	Proprietary format	Split baseband with scheduler in RRH and other baseband functions centralized
Carrier Outdoor (High Power) Small Cell	5.1W/ant-40W composite	Operator managed	Coordinated with macro layer, LTE or 3G gateway; some fixed wireless application
Carrier Outdoor (Low Power) Small Cell	300 mW to 5W per antenna. Below +52 dBm for mMIMO arrays	Operator managed	Coordinated with macro layer, LTE or 3G gateway
Carrier Indoor Small Cell	<300 mW per antenna	Operator managed	Lightly Coordinated with macro layer, LTE or 3G gateway
Distributed Radio System (DRS)	<300 mW per antenna	Operator managed	"Deeper" CRAN architecture where remote hub unit distribute IF signal to multiple radio units
Enterprise Small Cell	50 to 300 mW/antenna	Enterprise or Neutral Host purchased and managed	Autonomous node (Gateway) or local controller.
Residential Femtocell	<50 mW/antenna	Consumer or SOHO managed	Autonomous node (Gateway)

Source: Mobile Experts. NOTE: Mobile Experts has changed its definitions to simplify our language, calling integrated small cells and RRH units as "Small Cells".